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Implications of Radial Migration for Stellar Population Studies

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Abstract. Recent theoretical work suggests that it may be common for stars in the disks of spiral galaxies to migrate radially across significant distances in the disk. Such migrations are a result of resonant scattering with spiral arms and move the guiding centers of the stars while preserving the circularities of their orbits. Migration can therefore efficiently mix stars in all parts of the Galactic disk. We are rapidly approaching an important confluence of theory and observation, where we may soon be able to uncover signatures of such processes in our own Milky Way. The resolution and robustness of the physical modeling in simulations has improved drastically, while observational datasets are increasing in depth and astrometric accuracy. Here, we discuss the results from our idealized N-body/SPH simulations of disk formation and evolution, emphasizing specifically the observational consequences of stellar migration on the solar neighborhood and the vertical structure of the disk. We demonstrate that radial mixing of stars is a crucial dynamical process that we must try to understand if we are to draw significant conclusions about our Galactic history from the properties of stars in our vicinity.

1. Introduction

Disks of spiral galaxies are kinematically cool, rotationally-supported, self-gravitating systems made up of stars and gas. Stars form in the thin gas layer and begin their lives on mostly circular orbits due to the efficiency with which gas is able to shed excess energy. The stellar orbits are subsequently heated through interactions with giant molecular clouds (GMCs), external perturbations from infalling substructure, and resonances with disk structure. Observations of stars in the solar neighborhood show that velocity dispersion is related to stellar age by a power-law (Holmberg et al. 2009). Given that the epicycle amplitude in the solar neighborhood is limited by $\Delta R \simeq \sqrt{2}\sigma_R/\kappa$ (equation 3.99 Binney & Tremaine 2008, hereafter BT08), $\sigma_R \sim 50$ km/s (Holmberg et al. 2009) for the oldest stars in the solar neighborhood, and $\kappa_0 = 37$ km/s/kpc (BT08), the largest orbital excursions for stars at the solar radius are $\lesssim 2$ kpc. Averaged over the entire sample, the amplitude of radial oscillations $\Delta R \simeq 1.3$ kpc, allowing stars to traverse across ~ 2 kpc during a single orbit.

Such radial orbital oscillations of stars naturally affect the distribution of stellar population properties in the solar neighborhood. If regions of the galaxy evolve approximately as closed-box systems, then one expects there to be a tight relationship between the age of a star and its metallicity, the so-called age-metallicity relation (AMR) (Twarog 1980). Radial oscillations of stars dilute such a relation, and have been considered in the past to explain the large scatter in the observed AMR (Edvardsson et al. 1993; Holmberg et al. 2009). However, if we naively assume a relatively steady metallicity gradient over the past few Gyr of ~ 0.06 dex kpc^{-1} (Daflon & Cunha 2004), the dispersion of the stellar metallicity in the solar neighborhood arising solely from such orbital excursions should be $\lesssim 0.1$ dex. The observed dispersion in the AMR in the solar neighborhood is larger by at least a factor of 2 (Holmberg et al. 2009). Of course, the gradient could have been steeper in the past, but correcting for orbital eccentricities in the observed Geneva-Copenhagen sample does not explain away the large dispersion in the AMR (Nordström et al. 2004; Binney 2007).

The observationally-limited maximum epicycle amplitude of $\lesssim 2$ kpc leads to a picture of galactic disks where stars must remain relatively close to their radii of origin, only increasing their epicyclic energies in response to perturbations in the disk. The need for more substantial radial mixing was first discussed by Wielen et al. (1996), who argued that the Sun could not have originated at its present radius based on its anomalously high metallicity with respect to the surrounding stars and the local ISM metallicity. Sellwood & Binney (2002, hereafter SB02) spearheaded the recent resurgence in the interest in radial mixing by showing that radial migrations of even larger magnitude than that postulated by Wielen et al. (1996) are not only possible but very likely in the presence of recurring transient spirals. SB02 demonstrated that the migration takes place due to scattering at the corotation resonance of the spiral, but the large changes in the stellar guiding centers are not accompanied by significant heating. The lack of heating is important because mostly circular stellar orbits are typically assumed to have had a relatively quiet history - SB02 showed that this assumption is not necessarily true. Subsequently, Lépine et al. (2003) explored the orbital evolution of stars under the influence of corotation resonance; Roškar et al. (2008b,a) studied the effects of radial migration in a full N-body simulation of disk formation; Schönrich & Binney (2009a,b) were the first to incorporate these ideas into a chemical evolution model of the Milky Way; meanwhile Debattista et al. (2006) and Minchev & Famaey (2010) investigated mixing and heating via chaotic bar-spiral coupling.

We examine this paradigm further by means of self-consistent, though idealized in its initial configuration, simulation of disk galaxy formation. The results of this simulation have previously been reported in Roškar et al. (2008b,a, R08 collectively hereafter) and Loebman et al. (2010). In this contribution, we specifically focus on the importance of radial migration for studies using local (solar neighborhood) stellar samples to infer something about our Galaxy's past evolution (such as West et al. 2008; Bochanski et al. 2010; see also Bochanski, this volume).

2. The Simulation

The details of our simulation method have been discussed previously in R08. Here, we recall the salient qualitative aspects. The basic picture is one of a hot, spherical gaseous halo embedded in a massive dark matter halo, such as one might expect to exist after the last major merger for a Milky Way (MW) type galaxy. Thus, our model is initial-

ized with a spherical gas halo in hydrostatic equilibrium set by the potential well of a $10^{12}M_\odot$ dark matter (DM) halo. Both halos follow the same NFW profile (Navarro et al. 1997), but we impart a spin upon the gas corresponding to a cosmologically-motivated dimensionless spin parameter $\lambda = 0.039$ (Bullock et al. 2001). The two components are represented by 1 million particles each - this results in a mass resolution of $\sim 10^5 M_\odot$ for the gas and $\sim 10^6 M_\odot$ for the DM. We evolve the system with the parallel *N*-body + Smooth Particle Hydrodynamics code GASOLINE (Wadsley et al. 2004) for 10 Gyr. As the simulation proceeds, the gas is able to cool and collapse to the center of the potential well, forming a centrifugally-supported disk.

The crucial point here is that we do not insert by hand any properties of the disk. Instead, its final properties are a product of a complex interplay of various processes (gas cooling, stellar feedback, star formation, self-gravity). Our simulation code allows the gas to form stars once appropriate temperature and density are attained, thus forming a disk of stars self-consistently within our sub-grid star-formation framework. The stars in turn are modeled as evolving stellar populations, a fraction of which explode as supernovae (of type Ia and II), returning metals back to the ISM. We follow the yields of α elements and iron separately, allowing us to track gross abundance patterns.

Our model should therefore be regarded as a crude chemical evolution model coupled with self-consistent *N*-body dynamics. Since we do not set any properties of the disk a priori, our simulation is not a fit to the Milky Way. However, the simulation yields a disk that agrees qualitatively in many ways with the properties of our Galaxy. A critical concern is that the amount of structure that forms in the disk is unreasonable - should the amplitude and frequency of spirals be unusually high, this could result in unreasonable heating rates and unrealistic rates of migration. Importantly, the heating rates as derived from the age-velocity dispersion relationship in the model are even somewhat lower than the MW - power law fits give indices of 0.24, 0.21, 0.25, 0.37 for total, u, v, w dispersions respectively, compared with 0.40, 0.39, 0.40, and 0.53 for the same quantities derived for the solar neighborhood from the Geneva-Copenhagen survey (Holmberg et al. 2009). We speculate that the discrepancy arises from the presence of additional heating sources in the Galaxy, which are not captured by the simulation such as substructure (our disk evolves in isolation) and giant molecular clouds. In our model, the heating is primarily from spirals, and these numbers indicate that the amount of asymmetric structure is not unreasonable. Our simulated disk also yields a reasonably flat rotation curve, though it flattens at $\sim$ 240 km/s compared to 220 km/s for the MW indicating that the model is slightly more massive. The scale length of the simulated disk is 3.2 kpc compared to 2.6 kpc derived for the MW from SDSS data (Jurić et al. 2008), and the gas fraction is $\sim$ 10 %.

3. Radial Migration in Disks

On a Galactic scale, the solar neighborhood occupies a very small volume - the largest samples contain stars from a sphere only a few tens of parsecs in radius. It is therefore tempting to consider the grouping of stars around the Sun to be of a common origin, if not of direct relation through a common birth cluster (i.e. the “siblings” of the Sun Portegies Zwart 2009), then at least by virtue of having been born in the same part of the Galaxy. The latter assumption is made by virtually every chemical evolution model of the MW (e.g. Matteucci & Francois 1989; Carigi 1996; Boissier & Prantzos 1999; Chiappini et al. 2001).

Such assumptions, as we show below, oversimplify the dynamical evolution of stars in a galactic disk. Stellar orbits are profoundly affected by the spontaneous growth of spirals in a self-gravitating disk. The heating offered by such transient spirals has been extensively studied in the literature, and is required to explain the observed heating rates (BT08). However, transient spirals can also cause large changes in stellar orbital radii, while keeping the random energy of the orbit untouched, i.e. without heating (Sellwood & Binney 2002). This results in radial migration of stars, where individual radii in a MW-type disk can change by several kpc during the lifetime of the disk.

Figure 1 shows the probability density plot of formation radii as a function of final radii for the simulated disk at the end of the simulation. It is evident that the above assumption of stars found locally now being somehow related, is incorrect - whichever final radius one chooses, its stellar population is significantly contaminated by stars from other radii. The extent of this contamination is drastic - at 8 kpc, a $\sim$ 2% chance exists that a star has formed at a radius as small as 2 kpc.

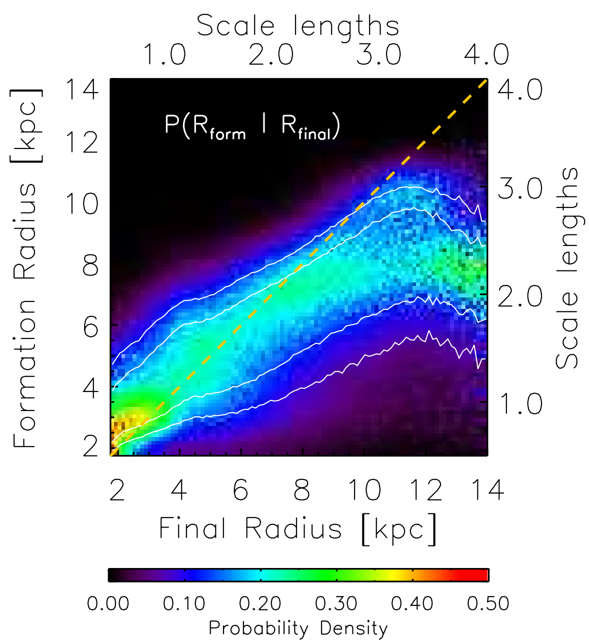

Figure 1. Probability density plot of formation radius given a final radius for stars in the simulation. The inner (outer) white contours enclose 50% (75%) of the mass. If radial migration was unimportant, the highest probabilities would concentrate along the dashed yellow 1:1 line.

For stellar population studies focusing on the solar neighborhood, the most important concern is how the narrow region around the Sun may be affected by such mixing. Due to the limited resolution of our simulation, we cannot isolate a single spherical region 50 pc in radius, but instead focus on the average properties of a "solar neighborhood" defined as radial annuli centered on 8 kpc with several different ΔR. Figure 2 shows the distributions of formation radii for these annuli. From the left panel, it is clear that the distribution is skewed to $R < 8$ kpc and that it is quite extended. A better measure of the contribution of stars born at smaller radii to the overall mix at the solar radius is given by the cumulative distribution function shown in the center panel.

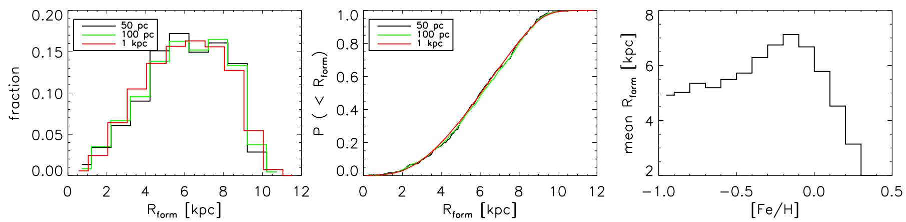

Figure 2. **Left:** Distribution of formation radii R_{form} for stars found in three different annuli centered on 8 kpc. The black, green and red lines show the distribution for annuli 50, 100, and 1000 pc wide respectively. **Center:** The cumulative distribution function of R_{form} for the same annuli. More than 50% of the stars come from $R < 6$ kpc. **Right:** Mean R_{form} as a function of metallicity. The ISM metallicity at 8 kpc is approximately Solar.

At least 50% of stars presently in the solar neighborhood have come from $R < 6$ kpc and $> 80\%$ of the particles currently in the solar neighborhood have come from radii smaller than 8 kpc.

In the right panel of Figure 2, we show the mean formation radii as a function of metallicity. Due to the fact that the disk grows from the inside-out, the majority of metal-rich stars therefore come from the interior of the disk. As a result, the high-metallicity end of the stellar distribution preferentially originates in the inner disk. Of course, because the local ISM metallicity is approximately solar, *all* stars with metallicities above solar must have come from another part of the galaxy, unless significant recent infall of pristine gas diluted the metals or the ISM is azimuthally very inhomogeneous.

Such distributions are of particular interest in light of the well-known planet-metallicity correlation for main-sequence FGK dwarfs hosting gas giants (Fischer & Valenti 2005). If the correlation is intrinsic (i.e. availability of planet-building material in the protoplanetary nebula) rather than a result of the pollution of a star's atmosphere by the accretion of one of the planets, the right panel of Figure 2 suggests that locally-found planet hosts should have spent considerable fractions of their lives in the interior of the Galaxy. Should the planet-metallicity correlation extend to hosts of lower-mass planets, the galactic history of such stars could have interesting consequences for the searches for signatures of extraterrestrial life (note that this correlation does not seem to exist for planets around giants, e.g. Pasquini et al. 2007; Ghezzi et al. 2010).

4. Vertical Evolution - Migrating into the Thick Disk

As stars move outward from the inner disk, they preserve their vertical energy, but the restoring force from the disk decreases due to the smaller surface density. Consequently, the amplitudes of their vertical oscillations also increase. The basic nature of this process is illustrated by Figure 3. At the midplane (top left), the stellar population mix is strongly influenced by local star formation so the majority of stars are locally born and relatively young. Note, however, that the distribution of R_{form} is very extended, as shown in Figure 2 (i.e. the projection of top left panel of Figure 3 along onto the y-axis). As we consider vertical slices at increasing heights from the midplane, the stellar populations become dominated by old stars that have come from the inner disk.

Fitting the vertical disk profile at 8 kpc with a double sech^2 profile yields two distinct components with scale heights of 381 pc and 913 pc, roughly consistent with the values found for the thin and thick disk of the MW (270 pc and 1200 pc Jurić et al. 2008).

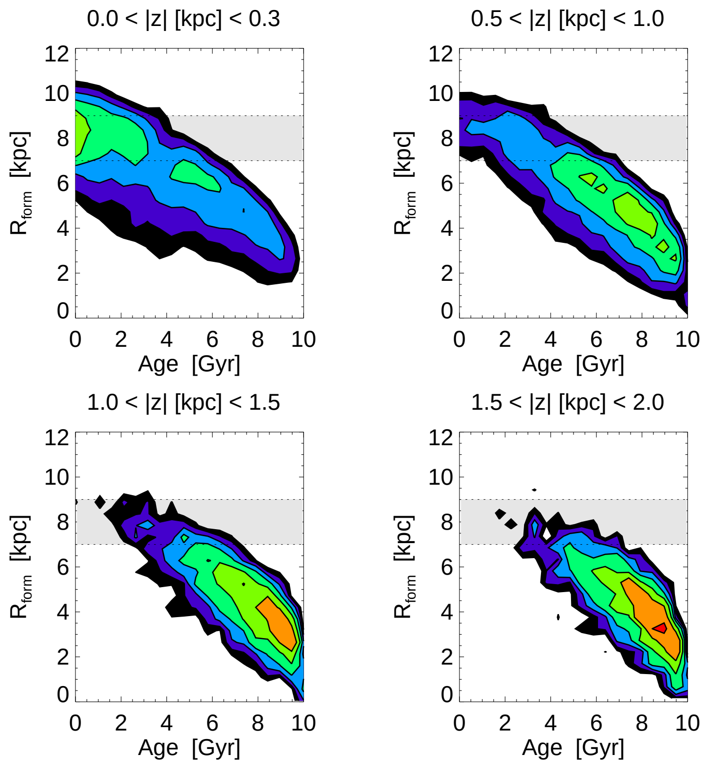

Figure 3. Distributions of formation radius vs. age for particles found in various slices above the midplane, in a 2 kpc annulus centered on 8 kpc (shown by the shaded region). Due to the high density of individual points, logarithmically-spaced contours are used as a proxy - colors indicate relative density, increasing from blue to red.

Because the disk grows and evolves, the birth environment of these migrated stars was quite different from their present surroundings. The metallicity gradient in the past was steeper (see Figure 2 of Roškar et al. 2008a), resulting in a large number of stars forming at low metallicity. The disk was also young and not yet polluted by supernova Ia metals so these old stars tend to be α-enhanced. As these stars are old, they have been heated through secular processes in the disk and therefore lag the local standard of rest. In short, the migrated population of old stars at the solar radius has all of the characteristics of the thick disk. See Schönrich & Binney (2009b) and Loebman et al. (2010) for more detailed comparisons between the properties of migrated stars and the observed MW thick disk.

In Figure 4 we show a part of this comparison. The left panel shows the Toomre diagram for the particles in the midplane at the solar radius. We select the thin and thick disk stars based on their kinematics, as is frequently done in the literature (e.g. Bensby et al. 2003, 2005), though because we do not know the kinematic properties of different components a priori we use a simple ad-hoc hard-cut dividing the thin

and thick disk at -70 km/s. Nonetheless, dividing the stars in this way gives us a rough idea of the interdependence between kinematics and chemistry. In the right panel of Figure 4, we show the α-element enrichment as a function of metallicity for the kinematically-identified thin and thick disk stars - the thick disk is enhanced, on average, in α elements, consistent with observational results for the MW thick disk (Bensby et al. 2005).

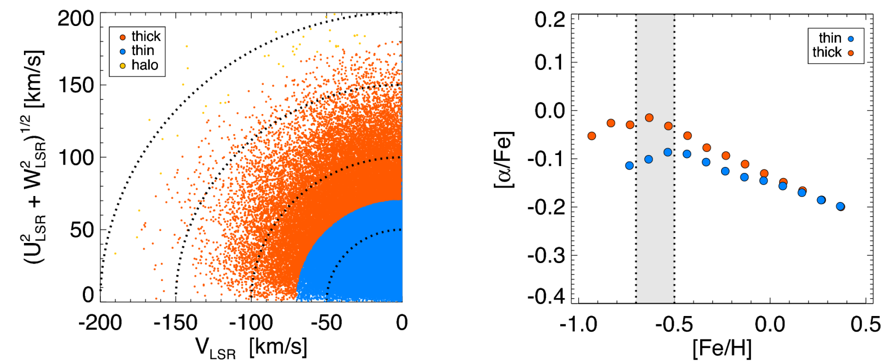

Figure 4. **Left:** Toomre diagram for stars in the midplane between 7-9 kpc. Color indicates a kinematic cut to define the thick and thin disks - stars with $V_{tot} \lesssim -70$ km/s are assigned thin disk membership, while stars with $-150 \lesssim V_{tot} < -70$ km/s are considered thick disk. **Right:** α-element enrichment as a function of metallicity of stars selected to be in the thick and thin disks based on kinematics.

Given the prevalence of sub-structure and streams found in the MW halo, presumably a consequence of the hierarchical merging process integral to the LCDM paradigm of galaxy formation, it is usually assumed that the thick disk is likewise a relic our Galaxy's cosmological history (see Wyse 2008 for a review). While we do not try to dispute the fact that our Galaxy is embedded in a tumultuous environment where disk-perturbing interactions are frequent, the fact remains that radial migration *will* contribute to the stellar populations found away from the disk plane. Radial migration must therefore be considered when assessing the cosmological significance of the stars found in the thick disk.

5. Conclusions

In galaxies with recurring spirals, stars do not remain near their birth radii. The guiding centers of their orbits can evolve drastically over the course of their lives. Conversely, no part of the disk in a spiral galaxy is free from contamination by stars that have come from other disk regions. Interpretations of stellar population properties found anywhere in the MW disk need to account for this fact. We have shown that in our models of MW-like disk formation, more than 50% of the stars have come from $R \lesssim 6$ kpc. The bias toward smaller formation radii is most pronounced at higher metallicities. Furthermore, we have argued that the migrated population also naturally forms a thick disk. This thick disk is in many ways reminiscent of the observed thick disk in the MW, yet its formation does not in any way depend on the galaxy's cosmological environment. Within the next decade, we can look forward to ground-breaking new surveys such as PanSTARRS, LSST and GAIA that will yield vast new datasets, detailing the structure

of our Galaxy. Combined with detailed dynamical models, such data will allow us to finally discriminate between the various scenarios for the formation of our MW disk.

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